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Russian Translation

Field Emission and Cold Cathodes

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Abstract: A survey and general analysis is given in this paper of the theoretical and experimental work in the region of field emission of metals and semiconductors and also the perspectives of the practical use of field emission are discussed.

1. Introduction

Among the various kinds of electron emission, the so-called field electron or 'cold' emission occupies a special place. If thermionic, photoelectronic and secondary electron emission have already been long and widely used in technical electronic devices, then we can speak about the practical uses of field electron emission at the present time, primarily, only as to its prospects despite the fact that this kind of electron emission has been known almost as long as the rest (as is known, field emission was disclosed in 1897 by Wood [1]).

Evidently, this can be explained by the field emission cathode, despite its numerous advantages over its rival - the thermionic cathode, being distinguished, for a long time, by its great instability, its poor reproducibility and its short life. Their extension was hindered by the necessity of using relatively high voltages for which the field emission current from the pure metal acquires a sufficiently high value.

Because of the above, the study of field emission took a path rather different from the path by which the knowledge of thermo-, photo- and secondary electron emission as well as progress in the construction of new thermo-, photo- and secondary electron cathodes were developed. If the latter kinds of emission and types of cathodes attracted a vast number of investigators, where the experimental investigations and attainments in creating new cathodes often outstripped

theoretical developments by far, then experimental investigations in the region of field-electron emission, considerably lesser in number, followed theoretical work to a large degree, with the fundamental problems of the experimental work being, for a long time, the verification of some conclusion of the theory. In recent years, in connection with the significant progress of vacuum technique which guarantees the possibility of increasing the stability of field-electron emission and of obtaining considerable field-electron current densities, interest in field-electron emission has been reactivated strongly, insofar as can be judged from the literature, where, in certain works, the question has been posed of the prospective technical uses of the cold cathode.

Basically, the development and modern status of work in the region of theoretical and experimental studies of the field emission mechanism are considered in this work, i.e., the emission of electrons by a solid body under the effect of an external electric field which owes its occurrence to the tunnel effect through the barrier on the boundary of the solid boundary and the vacuum, and prospective uses of field-emission cathodes in technical electronic devices are discussed.

Hence, for lack of space, questions related to the use of field-emission cathodes in electronic projectors, where they play the part of the objective, or the means to investigate various surface processes such, for example, as adsorption, evaporation and migration of both the intrinsic and the foreign atoms, are not touched upon. A number of phenomena is not considered, in which field-emission participates, among them: emission of thin dielectric films when an intense electric field is present therein; spark-over in a high vacuum; phenomena on the cathode in an arc discharge; phenomena on the contacts and in the volume of a substance which owe their occurrence to the tunnel effect (internal field-emission) etc. A majority of the work in these directions can be found

in relatively recent surveys [2-6] which, however, was published before a whole series of works appeared.

2. Early stages in the investigation of field-emission. The Fowler-Nordheim theory and its experimental verification

The development of the study of field-emission can be divided into several stages.

The early experimental work investigating field-emission, basically the work of Lilienfeld [7] and also of certain other authors, belongs to the first stage which starts from the moment of the discovery of field-emission, i.e., from 1897 and extending to 1922. A result of these works was the concept of field-electron emission as a very unstable and poorly reproducible effect.

The next stage starts with 1922, i.e., with the appearance of the well-known Schottky theory describing thermionic emission facilitated by an electric field. Attempts to extend the Schottky theory to the case of 'cold' emission under the effect of an intense field served for a while as the reason for setting up a cycle of experimental investigations with the intent of verifying the fundamental conclusions of this theory. The experimental facts observed here, such as: the field-emission being independent of the temperature in a broad range of T (from $300 - 1400^{\circ}$ K), the dependence $\lg J = f(\sqrt{E})$ being nonlinear, very obviously indicated the inapplicability of the Schottky theory to the case of 'cold' emission under the action of a field [8].

The start of the third stage in the development of the study of field-emission should be considered 1928, when the well-known works of Fowler [9] and Nordheim [10] were published, in which a dependence was obtained (for the $T = 0$ case) between the current of 'cold' emission and the intensity of the electric field acting on the surface of a metal cathode, on the basis of the Sommerfeld

electron theory of metals and the concepts of quantum-mechanical theory on the possibility of electron passage through the energy barrier at the cathode surface at the expense of the tunnel effect.

This dependence has the following form:

$$J = 6.2 \cdot 10^{-6} \frac{\sqrt{\mu}}{(\mu + \varphi)\sqrt{\varphi}} E^2 \exp\left[-\frac{6.85 \cdot 10^7 \varphi^{\frac{3}{2}}}{E}\right]$$

where J is the current density in amp/cm^2 ; E is the electric field intensity in v/cm ; μ is the maximum Fermi energy in eV ; φ is the work function in eV .

The Fowler and Nordheim theory was made more precise by Nordheim in 1929 by taking into account the effect of the forces of the mirror images [11].

The more precise formula is:

$$J = 1.55 \cdot 10^{-6} \frac{E^2}{\varphi} \exp\left[-\frac{6.85 \cdot 10^7 \varphi^{\frac{3}{2}}}{E} \theta\left(\frac{3.62 \cdot 10^{-4} \sqrt{E}}{\varphi}\right)\right]$$

where $\theta\left(\frac{3.62 \cdot 10^{-4} \sqrt{E}}{\varphi}\right)$ is a special function tabulated by Nordheim. In recent years, the values of this function have been made more precise [12,13].

The first attempts at a quantitative experimental check of the conclusions of the quantum-mechanical theory of field-emission [14] appeared to be failures since, because of the roughness of the field-emission cathodes being investigated (in the form of wires placed on the axis of a cylindrical diode system), the actual values of the field intensity at the surfaces of the separate microscopic projections appeared to be indefinite and not in conformance with the values of the field intensity computed by starting from a given potential difference and the macrogeometry of the electrode system.. Attempts to eliminate the influence of the roughness by using a liquid cathode [15] operating in the impulse region, also did not give positive results.

Success was attained first, just after Müller [16] obtained a perfectly

smooth (i.e., smooth to the accuracy of an atomic distance) surface of the field-emission cathode which was prepared in the form of a needle of tungsten or molybdenum by chemical etching of the wire with the subsequent heating of the needle thus obtained in a vacuum.

Considering the cathode-plate system as two confocal paraboloids of revolution, Muller determined the field intensity at the surface of the cathode, which was a needle with the radius of curvature* approximately equal to $0.6\ \mu$, and he obtained the value $E = 3.5 \cdot 10^7$ V/cm for a plate voltage of 8000 V and a current of 10^{-6} amp (corresponding to a 200 amp/cm^2 current density). Hence, a value, corresponding to that required by quantum-mechanical theory, was obtained experimentally for the first time for a field intensity causing a notable field emission.

The next big step along the path of experimentally confirming the quantum-mechanical theory of field-emission of metals was made by Haefer [17], who used an electron microscope to determine the shape and dimensions of the field-emission cathodes which were prepared according to the Muller method. Haefer made a quantitative verification of the Fowler and Nordheim formula for these cathodes, which consisted of determining the numerical constants A and B in the formula $J = AE^2 \exp\left[-\frac{B}{E}\right]$ in terms of the semilogarithmic characteristic $\lg \frac{J}{E^2} = f\left(\frac{1}{E}\right)$. The A and B values found experimentally in this way appeared to be in good agreement with their theoretical values (calculated according to the Nordheim formula by taking into account the mirror images for $\varphi = 4.5$ eV and $\mu = 5.71$ eV). Along with the experimental verification of the relation between the field emission current density and the electric field intensity resulting

* It should be noted that the needle radius in the Muller experiments was determined by using an optical microscope, i.e., was very inaccurate so that the Muller result is not completely reliable.

from quantum-mechanical theory, attempts were made to investigate the dependence of the field-emission on the work function of the cathode material [theoretically the slope of the characteristic $\lg \frac{J}{E^2} = f\left(\frac{1}{E}\right)$ must be proportional to $\varphi^{\frac{3}{2}}$]. The first works in this direction, in 1936, led to an erroneous result. However, in 1940, Haefer [17], superposing films of barium, potassium and cesium on the tungsten needle in both a thick and in a covering (monoatomic) corresponding to the optimal in the sense of lowering the work function, and determining the work function of the cathode in each separate case from the slope of the semilogarithmic characteristic, obtained data in very good agreement with the known values of the work function for the films investigated. Hence, the proportionality of the coefficient of the work function to the $\frac{3}{2}$ power, entering in the exponential of the Nordheim equation, received convincing experimental verification. It should be noted that the method of the Haefer work suffered from certain deficiencies: A hyperbolic approximation was used to compute the field, which is not a very exact method (for example, see [18,19]); the field-emission current was averaged over the whole emitter surface, where the averaging was carried out on the basis of the result of auxiliary experiments which introduced additional errors; the solid angle of the field-emission output was determined inaccurately; no attention was paid to the 'atomic configuration' of the surface. Subsequently, a number of investigators [20-27] obtained the volt-ampere characteristics of field-emission for various faces of single-crystal tungsten needles and calculated the work function for these faces. Hence, Dyke and Trolan [22], using the results for the work function of the various faces of single-crystal tungsten taken from the work of Nicols [23] on thermal emission, obtained very good agreement between the slope of the semilogarithmic characteristics found theoretically and experimentally.

A very convincing argument in favor of the correctness of the quantum-

mechanical theory of field-emission was the results of investigating the energy distribution of the field-electrons. A computation of such a distribution is given in [32,33]. The first experimental work in this region, due to Henderson [29] and Müller [30], showed that the maximum field-electron energy corresponds to the Fermi level for the cathode electrons, as should have been expected. However, the width of the distribution curve obtained by these authors is considerably larger than theory forecasts.

Subsequently, Müller [31], eliminating the sources of error related to the distortion of the electric field which occurred in the apparatus he had used before, repeated the measurements of the energy distribution of the field-electrons and he obtained a perfectly extraordinary agreement between the theoretical and experimental distribution curves. The Muller result is shown in figure 1 where the dashed curve is the theoretical distribution for $T = 0^\circ$ K and the solid line is the theoretical distribution for $T = 500^\circ$ K (approximately equal to the temperature at which the measurements were made). As seen from the figure, the experimental points lie almost exactly on the theoretical curves.

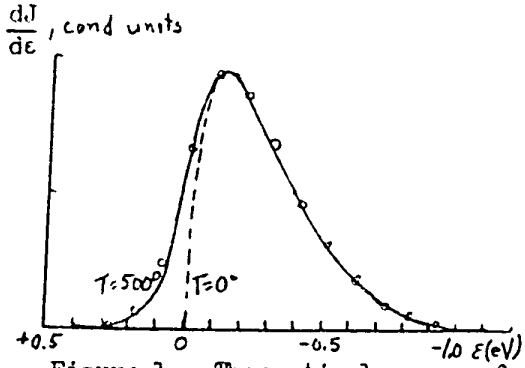


Figure 1. Theoretical curve of the field-electron energy distribution for $T = 0^\circ$ K and $T = 500^\circ$ K. The circles correspond to the experimental points.

Finally, the correctness of the quantum-mechanical theory of field-electron emission was confirmed experimentally by the fact, established by Müller [30] and later by Fleming and Henderson [34], of the absence of any noticeable cooling of the field-emission cathode as must certainly occur in the case of emission by thermally excited electrons. However, the heating of the emitter because of the

Nottingham effect [21], forecast by quantum theory, was not detected in these experiments although the sensitivity of the experiment was sufficient for this. Apparently, this is explained by the good elimination of heat from the end of the needle.

As seen from the above, the quantum-mechanical theory of field-electron emission has received completely satisfactory experimental confirmation for the case of relatively low temperatures and not too high current densities at the start of the fortieth year.

3. Temperature-Field Emission

The next step in the development of field-emission theory was the generalization made by Guth and Mullin [35] to the case of arbitrary cathode temperature and the presence of as intense a field as desired at its surface. The expression they obtained for the field-emission current density of a heated emitter is:

$$J = 1.55\cdot10^{-6}\frac{E^2}{\theta^2\varphi} + 120.54T^2\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n}\left(\frac{1}{n+8.813\cdot10^{3}\theta\varphi^{-\frac{1}{2}}\frac{T}{E}} + \frac{1}{n-8.813\cdot10^{3}\theta\varphi^{-\frac{1}{2}}\frac{T}{E}}\right)$$
$$\exp\left[-6.838\cdot10^{7}\frac{\varphi^{\frac{3}{2}}}{E}\theta\right]$$

where E is the field intensity in $^{V}/_{cm}$; φ is the work function in eV ; T is the emitter temperature in $^{\circ}K$ and θ is the Nordheim function. This relation is correct under the condition:

$$8.813\cdot10^{3}\theta\varphi^{-\frac{1}{2}}\frac{T}{E} < 1$$

Lukirskii and Tsareva [36] first made an experimental investigation of the dependence of the field-emission current on the field and on the temperature with the idea of confirming the Guth and Mullin theory. The results they obtained are in qualitative agreement with the conclusions of the theory. Regrettably, the quantitative agreement between theory and experiment was not established

The results of the computations are illustrated by the curves shown on figures 2, 3 and 4.

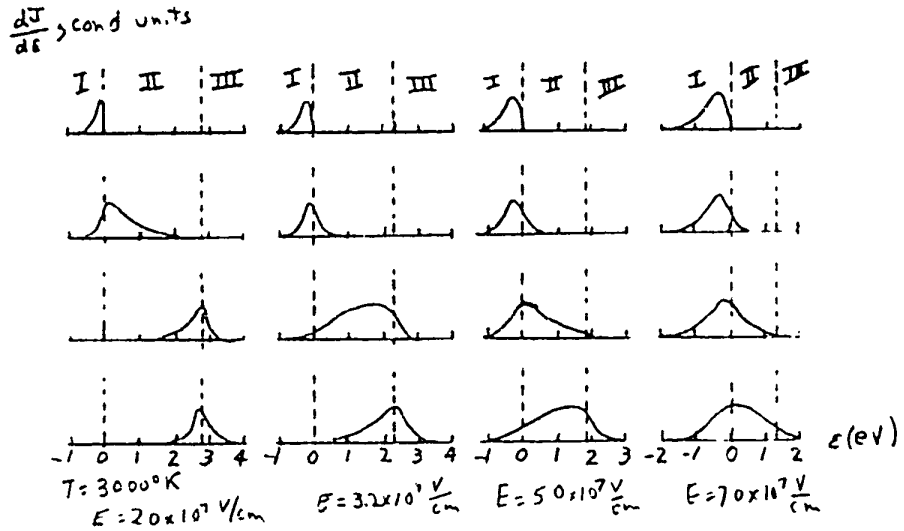


Figure 2. Theoretical energy distribution curves for field-electrons; $\Phi = 4.5$ eV . Abscissas in eV measured from the Fermi level at 0° K .

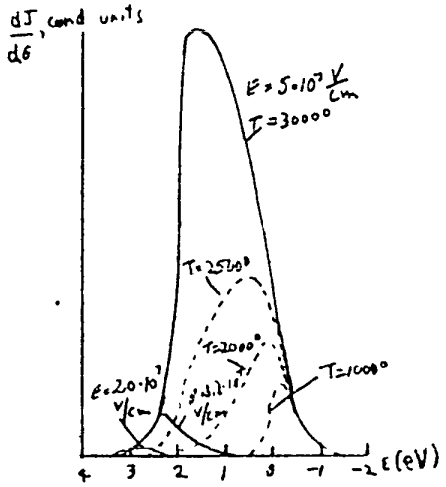


Figure 3. Theoretical curves of the energy distribution for the emitted electrons at 4.5 eV for various fields at T = 30000° K (solid line) and for the constant field E = $5 \cdot 10^7$ V/cm at various temperatures (dashed curves).

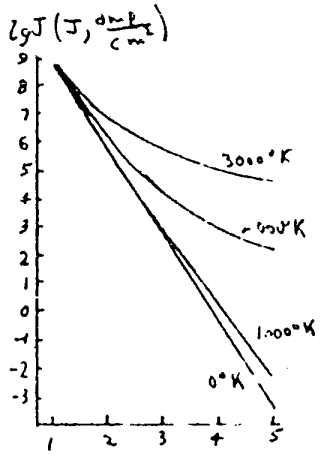


Figure 4. Theoretical dependence of the current density on the electric field at various temperatures. The quantity $\frac{10^3}{E}$ (E in $\frac{V}{cm}$) laid off along the horizontal.

Figure 2 shows the energy distribution of electrons calculated for various

temperatures (from 0° K to 3000° K) and fields (from $2.0 \cdot 10^7$ V/cm to $7 \cdot 10^7$ V/cm). The maximums of the curves are reduced to a common ordinate. The numbers I, II and III mark the regions corresponding to electrons emitted at a level below the Fermi level (I), at a level between the Fermi level and the peak of the potential barrier (II) and at a level above the potential barrier at the metal boundary (III). Shown on figure 3 are distribution curves for constant temperature (3000° K) and various values of the field intensity (solid lines) and for constant field intensity and various temperatures (dashed curves).

Figure 4 gives the dependence of the current density on the reciprocal of the field intensity constructed to a semilogarithmic scale. As seen from the curves, the influence of the temperature on emission is hardly perceptible down to temperatures of the order of 1000° K (which explains the independence, found at the time, of the field-emission on the temperature, for example, in this same interval of values of the latter). Only as the temperature is increased further does its influence on emission start to be expressed to any large degree, especially in the region of not too strong fields. All these results are completely reasonable, qualitatively, and require no further explanation.

Later in [39], an experimental verification was made of the computational formulas for the field-emission, averaged over the surface, of a tungsten needle in the $2.5 \cdot 10^7$ V/cm to $7 \cdot 10^7$ V/cm field range and for temperatures from 300° K to 2000° K. The needle geometry was examined by using an electron microscope and the appropriate computational formulas were used to determine the field intensity at the cathode surface (see [18]). The temperature was measured by an optical pyrometer and was checked by the thermoelectric current in the absence of the field. In order to decrease the role of temperature emission of the needle carrier, the latter was made very short and the temperature did

not exceed 2000° K . In order to eliminate rebuilding of the needle surface because of migration, the measurements were made during a very short time.

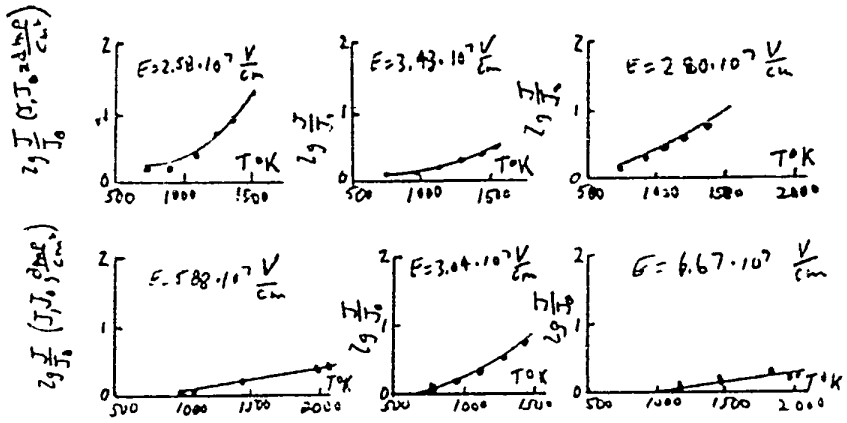


Figure 5. Theoretical curves of the dependence of $\lg \frac{J}{J_0}$ on T (° K) for several values of the field. J is the field-emission current density at a given temperature. J_0 is the same at 300° K . Experimental results marked by dots.

As seen from figure 5, the experimental results confirm the results of computations made by the method described in [38] if the appropriate corrections are introduced for the dependence of the work function on the temperature and for the variation of the needle geometery during the time of heat treatment. Apparently, there are no experimental results on the energy distribution of field-electrons for various field and temperature values in the literature.

4. Investigation of field-emission for high current densities

In the past several years, Dyke and his colleagues have published a cycle of works of not only purely theoretical, but also, of practical interest.

These works can be considered as the beginning of the fourth stage in the development of the study of field-electron emission characterized by the transition from the purely physical investigations to investigations with an explicitly expressed physical-engineering direction.

In one of the first of these works, published in 1956 [10] (preliminary reports were published in 1951 and 1952), the authors, taking into account that to obtain the highest possible current densities was an essential for practical applications, set themselves the goal of extending the investigation of field-emission to obtain the limiting current density values at which an arc discharge is usually observed in a vacuum.

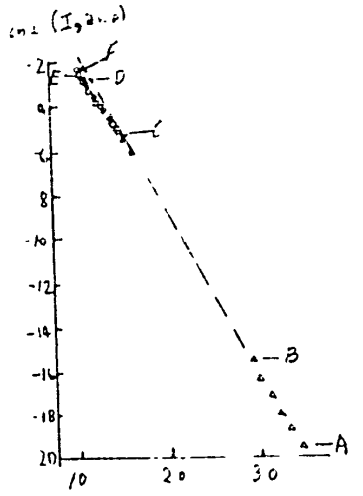
In order to stabilize the emission for such very high specific current loads at the expense of lowering the influence of such factors as cathode bombardment by positive ions, thermal heating, surface contamination, atom migration, etc., the authors used an impulse measurement method. In order to insure against cathode contamination by the residual gases, appropriate measures were taken to guarantee suitable purity of the materials used and a sufficiently high vacuum of 10^{-9} mm Hg during the unsoldering of the experimental tube and reaching 10^{-10} mm Hg and higher after absorption of the residual gas by the getter and after evacuation by an ionization pump.

All these measures guaranteed stability of emission for a time considerably in excess of that required for the measurements. Under these conditions, it appeared to be possible to obtain a stable constant current up to 8 ma for a field voltage corresponding to a cathode current density of the order of 10^{7} amp/cm^2. The authors remark that the limit to the further increase of the constant current was set by plate heating ($\sim$ to 1000° C) in this case, which led to the liberation of oxygen which contaminated the cathode surface with the consequent significant drop in emission per time.

It would be possible to record much larger currents in the impulse region (for microsecond pulses) were the cathode to remain uncontaminated.

A typical volt-ampere characteristic of field-emission, recorded partially at constant current, partially in the impulse region and constructed on a

semi-logarithmic scale, is shown in figure 6 (the triangles mark points obtained at direct current and the circles mark points obtained in the impulse region). As seen from the figure, the linearity of the $\lg J = f\left(\frac{1}{V}\right)$ dependence is conserved, starting with A and up to C. From C to D, the characteristic deviates from the linear, gradually, toward the lesser currents, which is a consequence of the volume charge formation, in the authors' opinion. Between D and E, the deflection of the characteristic again increases, which the authors say is due to temperature effect,



[illegible] typical curve of the dependence between the current and the voltage. The quantity laid off along the horizontal axis is $\frac{1}{V}$ (V in volts)

[illegible] emission caused by the cathode temperature increasing because [illegible] therein. The field emission makes the transition into a [illegible], which is characterized by an abrupt increase in the current and a simultaneous drop in the voltage at the electrodes [illegible]; the field-emission [illegible].

[illegible] the magnitude of the cathode emitting surface, the authors calculated the [illegible] corresponding to the points A and C on the [illegible], which are equal $J_A = $ [illegible] amp/cm^2 and $J = $ [illegible] amp/cm^2, respectively. The [illegible] (within the limits of the emitting surface) values of the field intensity [illegible], and [illegible] were computed by the method described in [illegible] for these values of the current density by starting from the cathode geometry and the corresponding values of the the plate potential V_A and V_C. Furthermore, using the Nordheim equation, the $J = f(V)$ dependence was computed

... values of ... for which the potential barrier on the cathode boundary is decreased to the height of the Fermi level. This dependence is shown on figure 7. The values of J_A and J_C found experimentally for corresponding values ... and ... are superposed on the same figure. As seen from the figure, the experimental points lie completely satisfactorily on the theoretical curve, which testifies to the applicability of the Nordheim formula in the range of current densities from one to one million ...

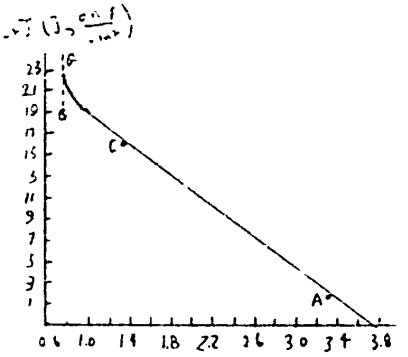


Figure 7. Calculated dependence of the current density on field intensity for ... The quantity ... is laid off along the horizontal. A and C are the experimental points.

... The stability of the space charge begins to be felt at current densities ... and stable field-emission makes the transition to a vacuum arc at a current density of about 10^8 amp/cm^2.

... consideration of an arc in a vacuum was considered in more detail in ... but was also published in ... Despite the contradictory nature of the results already existing, ... arrive at ..., on the basis of their experimental ..., that the fundamental factor governing the transition of the stable field-emission emission, depressed by space charge, into a vacuum arc is the critical current density, usually of the 10^6 amp/cm^2 order of magnitude, independently of the applied voltage (the experiments were made with field-emission cathodes of various kinds). Hence, the existence of the "total voltage effect" ... Trump and van der Graaff [16], which lowered the field intensity at which breakdown of the vacuum gap occurs as the applied voltage is increased, is rejected.

However, the authors emphasize that their results are real only under the conditions of a very high vacuum and purity of the materials used. In the authors' opinion, the mechanism of vacuum arc formation reduces to the cathode being heated by the high density currents flowing therein causing a further increase in emission (in conformance with the conclusions of the Muth and Mullin theory), with the final result being the evaporation of the tungsten. The arc discharge, leading to the melting of the tungsten needle, develops in the tungsten vapors ionized by the electrons. Using short-time (on the order of 1 μsec) impulses of high voltage, the authors showed that the gas ions liberated from the [illegible] participate in the formation of the arc. The transition of the stable field electron emission into the arc discharge is accompanied usually by an increase in the current of two orders. The characteristic pre-arc phenomena, according to the presence of which the achievement of the upper limit of the stable currents can be assessed, invariably precede the onset of the arc.

In a separate work [3], published simultaneously with that just cited, a computation was made of the variation of the temperature of the field-emission cathode during the process of removing field-emission current therefrom at the expense of liberating a clean heat by starting from the known cathode geometry. As a result of the computation it was shown that heating at the expense of only an heat is sufficient to melt the cathode at the critical current density $(\sim 10)^8$ amp/cm^2 which corresponds to the beginning of the development of the vacuum arc and that the heating process occurs extremely rapidly (within a time of the order of 10^{-7} sec).

In the same year, 1953, the work [4] appeared which contained an analysis of the influence of the space charge on the magnitude of the field-emission current taking into account that the well-known Langmuir equation, which assumes the field near the cathode equals zero, is not applicable here, the

authors, integrating the Poisson equation (for the plane case) under the assumption that the field is not zero at the cathode but equals E_0 and using the Nordheim formula in the form

$$J = cE_0^2 \exp\left[-\frac{b}{E_0}\right]$$

find the relation between the plate potential V and E_0:

$$4kc\sqrt{\frac{3}{2}} \exp\left[-\frac{b}{E_0}\right] - 3V = 9k^2c^2E_0^2d^2 \exp\left[-\frac{2b}{E_0}\right] - 3E_0d$$

where k is a proportionality coefficient which enters into the Poisson equation $\frac{d^2V}{dx^2} = -kJV^{-\frac{1}{2}}$; d is the distance between the electrodes.

The last equation and the Nordheim formula jointly permit the field-emission current density to be determined which is limited by space charge, for any value of the potential V.

The quantity d was chosen in the computations so that the field in the plane system (in the absence of space charge) would correspond to the field at the cathode under real conditions for a given value of the applied potential.

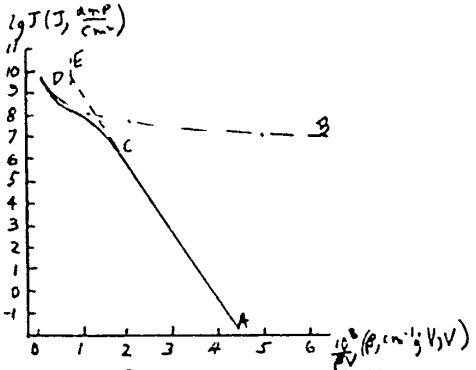


Figure 8. Dependence of the current density on voltage in the presence and absence of space charge.

Shown on figure 8 is the theoretical behavior of the dependence of the field-emission current density on the applied voltage computed without taking the space charge into account (curve ACE) and taking the space charge into account (curve ACD). Shown there for comparison is the dependence of J on V constructed according to the three-halves law (curve BD). As is seen, the curve ACD approaches BD asymptotically, running together with it for large V.

Figure 9 illustrates the result of comparing the computed (solid lines) and the experimental (points) dependences of lg J on the reciprocal of the field intensity. Curve 1 corresponds to pure tungsten; curves 2-4 to barium on tungsten for various degrees of covering (the values of the work function needed for the computations in the case of a barium film on the tungsten, were determined according to the slope of the semi-logarithmic characteristic in the small current region), curve 5 is constructed according to the three-halves law.

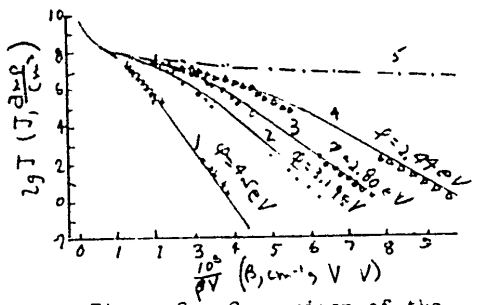


Figure 9. Comparison of the experimental data and the theory of field emission taking space charge into account. 5 - the Langmuir curve

As seen from figure 9, the agreement between theory and experiment appears to be completely satisfactory in the range of current densities from 2 amp/cm^2 to $4 \cdot 10^7$ amp/cm^2 while the theory not taking the influence of space charge into account was justified only for current densities not exceeding $6 \cdot 10^6$ amp/cm^2.

Finally, in 1965 the work [35] appeared which was devoted to the investigation of a field-emission cathode prepared from rhenium. Such a cathode appears to be insensitive to the presence of residual gases. As shown by observations made in the course of two weeks (using an electron projector) on the behavior of a rhenium field-emission cathode in the same envelope with a tungsten cathode, the surface of the first remained pure while the tungsten surface was covered rapidly by an adsorbed film. This result is of substantial interest from the point of view of the possibility of increasing further the stability of field emission cathodes.

As is seen from all the above, the field-electron emission of pure metals has been studied rather completely, to the present time, both theoretically and experimentally. Evidently, the development of the theory of field-electron

emission of metals can be considered, basically, completed and the conclusions of this theory can be considered confirmed by experiment to a sufficient degree. Nevertheless, it is necessary to note that the objects of investigation were not all metals by far. The most completely investigated was tungsten. Less completely studied are molybdenum and nickel. Only slightly investigated are tantalum, rhenium, copper, zirconium, silver, niobium, platinum, vanadium and iron.

b. Field-electron emission of semiconductors

Until recently, only the work of N. D. Morgulis [6] was known in the region of the theory of field-emission of semiconductors. One of the fundamental peculiarities distinguishing a semiconductor from a metal is taken into account in this work; namely, the capacity of an external electric field to penetrate within the semiconductor causing, thereby, an appropriate distortion of the energy zone of the cathode which leads to a decrease in the internal work function ζ by $\Delta\zeta$ (and, correspondingly, to an increase in the concentration of the conduction electrons at the cathode surface) in addition to a decrease in the external work function χ by $\Delta\chi$ so that the total work function φ decreases by $\Delta\varphi = \Delta\zeta + \Delta\chi$ (figure 10). Limiting himself to the case of not too high fields ($E \leq 5 \cdot 10^{5}$ v/cm) when the electron gas in the conduction band remains non-degenerate, neglecting the influence of the electric mapping force and without taking into account the possible deformation of the energy band of the semiconductor at the expense of the electron surface states, N. D. Morgulis obtains the following expression for the field-emission current from a semiconductor.

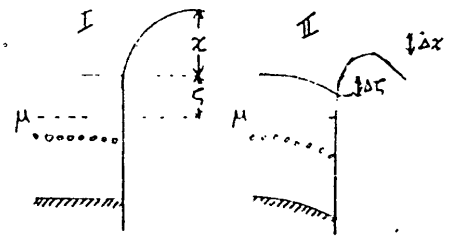


Figure 10. Energy diagram of a semiconductor without field application (I) and with an applied field (II).

$$J = J_1 + J_2$$

where

$$J_1 \cong A \exp\left[\frac{\Delta\chi}{kT}\right] \exp\left[-a\frac{\chi^{\frac{3}{2}}}{E}\right]$$

and

$$J_2 \cong c \exp\left[-\frac{a(\varphi_1 + \alpha\frac{1}{2}\Lambda)^{\frac{3}{2}}}{E}\right]$$

Here, $a = 6.8 \cdot 10^7$; Δ is the width of the occupied band; $\varphi_1 = (\chi + Q)$ is the photo-electric work function; $0 \leq \alpha \leq 1$. The J_1 and J_2 components of the field-emission current correspond to: the first to the electron current passing through the barrier from the conduction band; the second to the electron current supplied by the occupied band. For not too strong fields, the J_1 component plays a fundamental part.

It should be noted that the whole series of assumptions made by N. D. Morgulis to simplify analysis of the problem, naturally, must limit the region of application of the result obtained.

Stratton [47] recently published a work devoted to the further development of the theory of semiconductor field-emission by analyzing the same problem in a more general form without the limitations made by N. D. Morgulis.

Stratton, in his work, derived formulas determining the field-emission current density for the following cases:

1. Surface levels absent; external field does not penetrate the semiconductor. In this case, if the effect of the mirror images are not taken into account, the expression obtained for the current density is:

$$J \cong e n \frac{2kT}{\sqrt{2m\chi}} \exp\left[-\frac{4}{3}\frac{k_0}{E}\chi^{\frac{3}{2}}\right]$$

and taking into account the mirror images yields:

$$J = e n \sqrt{\frac{kT}{2\pi m}} \exp\left\{-\frac{4}{3}\frac{k_0}{E}\chi^{\frac{3}{2}}\theta\left[\sqrt{\frac{\varepsilon - 1}{\varepsilon + 1}}\ \frac{e\sqrt{E}}{\chi}\right]\right\}$$

Here n is the concentration of free electrons in cm^{-3} ; k is the Boltzmann constant; ε is the dielectric constant:

$$k_0 = \left(\frac{8\pi^2 m}{h^2}\right)^{\frac{1}{2}} \approx 5.15 \cdot 10^7 \ (e/)^{-\frac{1}{2}} \ cm^{-1}$$

the rest of the notation is as before.

2. Surface levels are absent, the external field penetrates the semiconductor. Two cases can occur here. If the external field is insufficiently large so that Maxwell statistics for the electrons near the semiconductor surface would appear to be inapplicable (the bottom of the conduction band is located above the level of the chemical potential by a quantity considerably greater than kT), then the solution of the problem leads to a result analogous to that obtained by K. D. Morgulis. According to the Stratton estimate, this result must be correct for $E \ll \sqrt{\varepsilon} \cdot 1.5 \cdot 10^6$ V/cm .

If the external field deforms the energy bands of the semiconductor so much that the bottom of the conduction band at its surface is located below the level of the chemical potential by a quantity considerably larger than kT (according to Stratton, for $E \gg \sqrt{\varepsilon} \cdot 1.2 \cdot 10^6$ V/cm) then the electron gas in the region of the semiconductor which adjoins its surface becomes degenerate. In this case, the expression obtained for the current density is:

$$J \approx \frac{e}{4\pi^3} \frac{\chi^2}{\chi} \exp\left(-\frac{1}{3}\frac{k_0}{E}\chi^{\frac{3}{2}}\theta(u)\right) \cdot \exp\left\{\frac{2k_0 v \chi^{\frac{1}{2}}}{E^{\frac{1}{3}}}\right\} \cdot \left(1 + \frac{2k_0 v \chi^{\frac{1}{2}}}{E^{\frac{1}{3}}}\right)$$

where

$$u = \left(\frac{\varepsilon - 1}{\varepsilon + 1}\right)^{\frac{1}{2}} \frac{e\sqrt{E}}{\chi} ; \qquad v = \varepsilon^{-\frac{1}{2}} 3.[illegible] \cdot 10^7 \ [illegible]^{\frac{1}{3}} \ cm^{\frac{4}{3}}$$

The conditions to be fulfilled here must be:

$$1.2 \cdot 10^6 \sqrt{\varepsilon} \ll E \ll 3.4 \cdot 10^7 \chi^{\frac{3}{2}} \theta(u)$$

Regrettably, the theory does not analyze the intermediate states of the semiconductor between complete absence of degeneration and intense degeneration

of the electron gas.

3. The presence of charge occupying the surface levels and leading to the appearance of an internal barrier at the semiconductor surface φ_o [48] (fig. 11) is taken into account. In this case, the theory gives the following expression for the field-emission current density:

$$J = en\sqrt{\frac{kT}{2\pi m}}\exp\left[\frac{V}{kT}\right]\exp\left[-\frac{4}{3}\frac{k_o}{E}\chi^{\frac{1}{2}}\theta(u)\right]$$

This expression differs from the expression obtained for the case of surface levels absent (under the assumption that the external field does not penetrate the semiconductor and taking the effect of the mirror images into account) by the factor:

$$\exp\left[\frac{V}{kT}\right]$$

where V is the variation in the height of the internal barrier caused by the external field. Computations of the values of V are made in [47].

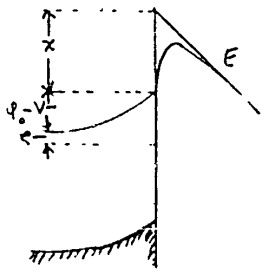


Figure 11. Internal barrier created by charges of the surface states and by external field variation.

By assigning acceptable values of the parameters entering into the relations obtained for the field-emission current density, Stratton carries out a computation of the dependence of $\lg J$ on $\frac{1}{E}$ for all the cases he analyzed. The results of the computation are shown on figure 12.

Here, curve I is obtained from the relation derived for the first case without taking the mapping force into account; curve II is from the relation for the same case but taking the mapping force into account; curve III corresponds to the case of field penetration into the semiconductor which leads to degeneration of the electron gas at its surface; curve IV corresponds to the presence of an internal surface barrier specified by the surface levels. The

curve IV is of special interest. For weak fields, it passes below curve II since the electron yield here is made difficult by the presence of the relatively high internal barrier. However, as the field increases further, the shielding effect of the surface charge at the surface energy levels, attenuates, consequently, emission increases here considerably more rapidly than in all the rest of the cases where curve IV intersects curve II for a certain value of E (in this case, $E = 2.5 \cdot 10^7$ V/cm), which testifies to the complete disappearance of the internal barrier ('puncture of the barrier'). For fields much higher than this critical value, the field bends the energy band in the opposite direction and the current varies in conformance with the relation obtained for the case reflected by curve III .

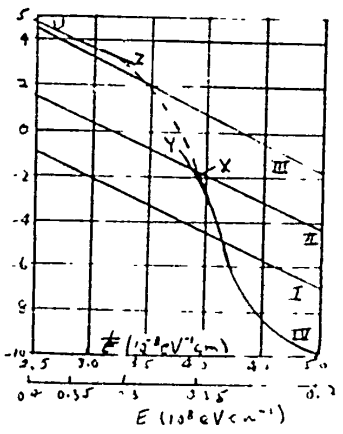


Figure 12. Dependence of field-emission current density from the semiconductor on the field.

The Stratton work and the work of M. D. Morgulis have laid the foundation of the theory of semiconductor field-emission. This theory awaits experimental verification which, probably, will be one of the objects of experimental work on field-emission in the near future.

Hence, if the theory of semiconductor field-emission can be considered to have been advanced sufficiently far after the publication of the Stratton work, then the matter of experimental work in this region is considerably less secure.

Insofar as we know, three investigations on this question have been published in the literature. The first of these is by Brezhnev [49], the second by Apker and Taft [50] and the third by Schleicher [51]. As is known, Brezhnev studied the electron emission of an antimony-cesium photo-cathode. Regrettably,

the roughness of the cathode made the determination of the true value of the field intensity at the cathode impossible. Consequently, a quantitative comparison of the results obtained by Brezhnev with the conclusions of the theory is not possible. Qualitatively, the character of the variation of the emission with the field in the Brezhnev experiments, apparently, corresponds to the case illustrated by curve III on figure 12.

However, inasmuch as it is not clear whether the micro-relief of the surface of the antimony-cesium cathode remained invariant during the measurement, it is difficult to conjecture how far such a qualitative comparison is valid.

Phenomena are described in the Apker and Taft work which are observed in the case of field-emission of needle-shaped single-crystals of CdS (or CdSe). The high sensitivity of the emission current to illumination which excited photoconduction in the CdS is established during the experiments. The authors refer this to the decrease in the resistance of the photo-semiconductor and to the related increase in the field intensity at the point of the needle-shaped single-crystal. The field-emission of an iron needle covered by an oxide film, Fe_3O_4 was studied in the Schleicher work. Insensitivity to adsorption of just the kind that was observed for pure rhenium is characteristic for emission from such a film.

Just as the Brezhnev work, the two last works do not afford the possibility of comparing results with theory nor also of making a quantitative comparison with field-emission from metals.

As regards the field-emission of dielectrics, to obtain some noticeable emission current here requires the presence of not an external field so much as a sufficiently strong field within the dielectric itself so that, first of all, its conduction would become large enough. The mechanism of the phenomenon which occurs herewith both in the dielectric itself and on its contact surface with

the metal electrode is similar, to a considerable degree, to the mechanism of the phenomenon observed in dielectrics in the pre-breakdown state. Consequently, the question of field-emission of dielectrics must be considered in common with the whole complex of questions referring to the theory and the results of experimental investigations of the pre-breakdown state and puncture of dielectrics. Inasmuch as these questions are beyond the scope of the present paper, electron emission of dielectrics, caused by a strong field, will not be considered here.

6. On prospective practical uses of field-emission

In conclusion, let us touch briefly upon the question of the possibilities and the prospects of practical use of field-emission.

It is well-known that, starting with 1937, field-emission cathodes began to be used widely in electron projectors, being a very valuable instrument for various physical and physico-chemical investigations, among them to study the field-emission itself (the observation of the stability of emission in terms of the stability of the image obtained on the projector screen; observation of the field-emission of various sections of the cathode surface, etc.) and also to investigate various surface processes occurring on the single crystal faces under various conditions such as, for example, adsorption and evaporation of atoms of foreign substances; migration of surface atoms, etc. (for example, see the work of Shuppe and his colleagues [52] and also of a number of other authors). The use of a field-emission cathode in an electron projector guarantees the possibility of obtaining an extremely large amplification (several million times) of the image with relatively high brightness and very high resolving power.

The field-emission cathode in electron projectors is, however, the instrument, if not the object, of investigations. Moreover, the field-emission cathode has a number of valuable qualities which can make it a serious competitor

of the thermionic cathode, which is in such widespread use in technical electronic devices, in the very near future. Among these qualities is the absence of the expenditure of energy which is necessary to the thermionic cathode to maintain a high temperature and, moreover, the absence of a required filament supply which is related to a gain in the efficiency of the device; the decrease in the bulk and weight of the installation in which it is used and also the elimination of difficulties relating to the necessity to isolate the filament supply in cases when the cathode is at a high negative potential with respect to the ground. A very substantial advantage of the field-emission cathode is that it does not require time to be heated and is always ready to operate. Another practical advantage of the field-emission cathode is the possibility of removing extremely high current densities (up to 10^8 amp/cm^2), approximately one million times greater than the maximum emission current density for a thermionic cathode. This permits relatively large currents to be obtained from cathodes with extremely small dimensions (Dyke [53] indicates that a current of several amperes can be obtained from a field-emission cathode which can be discerned with difficulty in a good optical microscope).

This latter fact discloses new possibilities to constructors of electronic apparatus, in particular, of apparatus in the ultra-high frequency range where the questions of obtaining high current densities and small bulk in the electrode system play a very essential role, as is known.

The field-emission cathode is, in the complete sense of the word, a point cathode which makes the prospects of its use in electron-optic systems, used cathode ray devices when it is required to obtain especially small cross-sections of the electron beam, very alluring. The field-emission cathode will probably be more stable with respect to impact and jolting in comparison to the thermionic. Finally, in certain cases, the extremely high sensitivity of the field-emission

cathode with respect to the plate voltage variation can appear to be of practical importance, i.e., the extremely high steepness of the volt-ampere characteristic of field-emission.

Despite all these positive qualities, the field-emission cathode has still not attracted the attention of constructors of electronic apparatus. The instability, poor reproducibility and short life-time of the field-emission cathode, as was remarked above, hindered its practical application for a long time. Among the field-emission investigations described above, the fundamental causes of these deficiencies were established successfully, where, as was mentioned, among these there are: 1. Adsorption of residual gases, as well as gases liberated from the electrodes and envelope of the device which would lead to a variation in the cathode work function and, besides, in the emission current. Here, because of the migration and the variation of a number of adsorbed atoms, current fluctuations, similar in effect to flickering, usually occur; 2. Cathode bombardment by ions of the recidual gases and also by the gases liberated from the electrodes and envelope which leads to an irreversible variation in the cathode geometry and a related variation of the field intensity for the separate elements of the cathode surface for an invariant potential difference on the electrodes and, therefore, to a variation in the emission current; 3. Migration of the intrinsic atoms over the cathode surface, variation of the cathode geometry under the action of the ponderomotive force of the electric field, evaporation and fusion of the cathode under overloading.

As regards the last reason for instability of the field-emission cathode, it can be eliminated easily by a suitable choice of its operating region. The first and second reasons are more difficult to eliminate. However, the effect of these reasons can be lowered considerably, at the present stage of vacuum technique, by using pure enough materials, by degasifying them carefully and

by creating the highest possible evacuation (a vacuum of the order of 10^{-9}-10^{-12} mm Hg and higher). The use of these measures at the present time enables field-emission cathodes to be obtained which operate with complete stability for at least several hours of both continuous and pulse operation. However, inasmuch as maintaining such high vacuums in engineering electronic devices is difficult at the present time, and stable cathode operation must occur through a very long period, Dyke in one of his latest papers [53] recommends using field-emission with a pre-heated tungsten cathode inasmuch as the tungsten cathode will not adsorb residual gases in the heated state. In order to decrease the influence of ion bombardment and cathode heating by the currents flowing therein, it is recommended that the field-emission cathode be used in the impulse region. According to the Dyke communication, he observed stable field-emission current of 0.2 amp from a pre-heated tungsten needle in the impulse region (microsecond impulses with a 300 impulse per second repetition rate) through 200 hours.

It is essential to note that a number of reports, at recent conferences devoted to field-electron emission [54], was devoted especially to questions of emission stability where these reports included information on devices using field-emission cathodes operating stably.

It is indisputable that the fundamental direction of the work in this direction is the correctly placed search for such substances which would have sufficient resistance against ion bombardment and adsorption as well as the use of any other methods which would decrease the intruding action of the above-mentioned factors.

Also important is the search for sufficiently rugged and stable substances with a lowered work function.

7. Conclusions

Summarizing, we can give the following characteristics of the modern state and the prospective further work in the region of field-electron emission:

1. The quantum-mechanical theory of the field-emission of metals can be considered perfected in its general characteristics. This theory has withstood all kinds of experimental checking and has received a completely satisfactory experimental verification. As the object of further work, it would be possible to recommend making more detailed investigations of the energy distribution of field-electrons for various values of the temperature and field intensity. Moreover, it is desirable to extend the investigation of field-emission to a broader circle of metals.

2. The theory of field-emission of semiconductors has progressed considerably, however, experimental work in this region is almost completely missing. It should be recommended, in every way, to set up experimental investigations of the field-emission of semiconducting materials both with the idea of verifying the theoretical conclusions and with the idea of seeking new field-emission cathodes suitable for practical use.

3. The technique of obtaining relatively stable, reproducible and long-lived field-emission cathodes has progressed comparatively far (but has still not been developed completely), which makes actual, in the more-or-less close prospect, the formulation of the question of using field-emission in certain technical electronic devices. The search for means to increase further the stability of field-emission cathodes must be one of the foremost problems of research workers in the near future.

Dec., 1955

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Recent Field Emission Literature in Russian

1) D. V. Zernov and M. I. Elinson, Field Emission and Cold Cathodes, Rad. i Elek. 1, 5 (1956). Abstract: A survey and general analysis is given in this paper of the theoretical and experimental work in the region of field emission of metals and semiconductors, and also the perspectives of the practical use of field emission are discussed. (Translation by Friedman for LRI is available. It is notable that this survey article, apparently intended to stimulate further work in the field, contains a good bibliography of non-Russian references but almost no previous Russian papers are cited.)

2) G. V. Spivak and A. Gal'berg, Study of the Auto-Emission of Electrons by Nickel, Dokl. Akad. Nauk USSR 94, 455 (1954). Abstract: The topic has been studied earlier by Müller (1937-8) and by Tsarev (1948) but the present authors introduce refinements and go further in (a) studying the effect of H on the Ni particle, (b) studying the change of the auto-emission of Ni when passing through the Curie point, (c) measuring the angular distribution of current density of a heated Ni single crystal. Comparison of results with the theory of Stanski and Suhrmann (1948) shows divergences.

3) I. L. Sokol'skaya, Surface Migration of Tungsten Atoms in an Electrical Field, Zh. Tekh. Fiz. 26, 1177 (1956). Abstract: The apparatus used was the conventional spherical projector 8 cm dia. with a tungsten point, the anode being an "Aquadag" layer on glass. The fluorescent screen was obtained by coating a wetted bulb surface with willemite without using any binder. The rates of the structure-transition and smoothing processes were determined as the reciprocals of the times of the transitions. It was found that these processes can be characterised quantitatively by changes in the field emission current at fixed potential, the time of the complete structural transition being determined as that in which the current attains a constant value. The structure-transition process does not depend on the field sign; hence the metals whose atoms migrate on the metal surface in an electrical field can be treated as dipoles moving along potential gradients. The structure transition in a field of the opposite sign makes it possible to protect the point against ionic bombardment and to carry out the experiments in very strong fields without causing the point to be melted by the electronic current. The energy of activation of the structure transition and the smoothing process were determined to be 2.36 and 3.2 eV, respectively. The obtained data, when interpreted in accordance with the theories of Frenkel and Stranski and Suhrmann yield values of interaction between two adjacent W atoms in the crystal lattice, which agree with those obtained from the heat of evaporation.

4) M. I. Elinson and G. F. Vasil'ev, Auto-Electronic Emission of Tantalum, Zh. Tekh. Fiz. 26, 1669 (1956). Abstract: A brief account of experimental investigation of tantalum (in the shape of a pointed wire) up to 2000°K and its comparison with tungsten is presented, illustrated by several microphotographs. The main conclusions are that at 1600°K the surface is freed from all adsorbed gas atoms and that oxygen adsorbed at the cold tantalum electrode tip considerably reduces the emission but surface oxidation achieved by heating the tip in oxygen atmosphere does not materially affect the emission properties. (Translation by Friedman for LRI is available)

5) Gorbatyi, Reshetnikova, Sytaya and Shuppe, The Electrostatic Emission from a Tantalum Single Crystal, Zh. tekh, Fiz. 27, 296 (1957). Abstract: Spherical projectors were made up with Ta points. A specimen etched with 90% HF and 10% HNO_3, used in vacuum conditions approximately 10^{-11} mm Hg, heated to 2600° K, gives a picture exactly corresponding to those for W and Mo. Photographs are given for a specimen in a variety of conditions such as: insufficiently annealed, heated at 2600°K, heated to 1000-1100°K, specimen with soiled surface. Treatment of the point by a reversed field leads, in the case of Ta, to a considerable increase of emission current.

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Research in Autoelectronic Emission of Lanthanum Hexaboride

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It is evident that the autoelectronic cathode of lanthanum hexaboride allows one to draw considerable stationary (~10 ma) and impulsive (~1 a) autoelectronic currents, which correspond to current density ~10^7 a/cm^2. With the help of an electronic projector, an emission picture of the boride is received. Investigated are the adsorption properties on the boride surface and its stability against ionic bombardment. Additional details indicate against the idea of boride as a coated cathode. It shows that with high temperature processing, the characteristic smoothness due to migration on its surface is not observed, in difference from metals. It is established that the volt-ampere characteristics correspond to the theory of auto-electronic emission in metals.

Introduction

Up to the present time research in auto-electronic emission has been done only in metals. It is established that one of the principal unavoidable reasons that shortens the life of auto-electronic emitters, is the cathode sputtering of the emitter substance, to which the auto-electronic emission is more sensitive than thermo-electronic.

But metals, among them the refractory, appear by far not the most stable substance against cathode sputtering. Naturally, one must turn attention to the possibility of such durable, refractory and stable substances as the carbides, borides and nitrides of metals.

It appears that for some of these substances exceptional durability is combined with low work function (ZrC, HfC, GdB_6, $Y B_6$, $La B_6$). The last one is especially attractive for research into the nature of these substances as auto-electronic and thermo-auto-electronic emitters.

It is known that thermo-electronic emitters originating from certain substances of the described type have not received, so far, wide-spread attention because of the cost, which cannot be an obstacle in auto-electronic emitters.

We can assume that the utilization of the above mentioned substances, about the emissive properties of which in general there is very little information, will establish a new stage in the development research of electronic emitters.

The goal in the present work, which is devoted to the research of auto-electronic emission of LaB_6, is to investigate peculiarities in the emission mechanism, adsorption properties, stability against ionic bombardment, also problems about the stability of geometrical form of the emitters while being prepared in vacuum.

Apparently this is the first attempt in this direction.

The initial object of research appeared to be points LaB_6 (cross section $\sim 1.5 \times 1.5$ mm and in length ~ 20 mm) cut with the help of electro-erosion from larger points. The latter were obtained from boride powder through hot pressure.

To get these points several chemical etchings and conditioners were used. The best results followed electrolytic etching by a continuous current in concentrated purified sulfuric acid with frequent check in the optical microscope. Subsequent baths in ammonia are expedient Rather smooth points are obtained by utilizing great current density (50 - 150 a/cm^2) in pulses (length of impulse ~ 0.5 sec) Illustration 1, as an example are shown electronic and optical microphotographs of the points after electrolytic etching. In Illustration 1-b, the outline of individual crystals of boride are well shown.

Illustration 1. Microphotographic points from LaB_6: a, optical; b, electronic.

To heat the emitter without destroying it presents well known difficulties. Illustration 2 depicts the methods we applied in strengthening and heating boride. Here are also shown the applied construction of the experimental apparatus.

Illustration 2. Construction of emitters and experimental instruments (emitters, anodes, protected spiral, fluorescent screen).

Heating the boride was achieved by calculating the heat conductivity (Fig. 2-a) or with direct passage of the current (Fig. 2-b), or electronic bombardment (Fig. 2-c) Most often combined heat was used.

The instruments were auto-electronic diodes with anode in the form of tightly wound basket of tungsten wire (Fig. 2-d), or like Müller's projector of different construction (Fig 2-e) In the majority of cases the protecting spiral OC was applied which protects the cathode foot and glass tube from the electronic bombardment, and focuses the electronic current on the emitter during the bombardment, with the purpose not to destroy it.

In the majority of cases with average temperature in heating (1000 - 1300°C) at the surface of the boride a thin, stable dielectric film is formed (more exact, a series of dielectric islets) the presence of which can be recognized by the characteristic change of color in the emitter and its impossibility to conduct an electronic bombardment. The deep, rich violet color, characteristic of pure boride, changes more often to turquoise tint (although other colors can be seen). This film can hold without strain up to 1 kilovolt and appears as the source of a sharp unstable auto-electronic emission. There is no doubt, the reason for the vacuum arc is the sharply strengthened field, which is caused by the positive charges stored on the surface of the dielectric film.

Spectral research, also analysis of possible chemical reactions and physical appearances, show that this film possibly represents the oxide of lanthanum.

To set the film completely free occurs at a temperature of about 2000°C. During this process the emission obtains an extremely stable character. The stability of the emission appears also after the above described vacuum arc, which apparently cleans the surface of the emitter. A characteristic peculiarity of highly (that is at 2000°C) heated emitters is that they give a very great emission current at relatively low voltage (for example: 5 ma at 4 kilovolt, while emission often begins at 1.5 to 2 kilovolt) and with comparatively big diameters at the very end of the point (usually 4 - 6 microns). At such high temperature a rather interesting evaporation of boride takes place. In many instances, because of the strong evaporation, the macroscopic diameter of the point was very large (about 100 microns), and in spite of this, the auto-electronic emission began at rather low voltage.

Illustration 3. The appearance of irregularities on the surface of the emitter after heating at temperature of 2000 to 2100°C.

All this compels us to assume that at high temperature on the surface of the emitter appear irregularities of small dimensions. On the electronic microphotographs (Ill. 3) it is obvious that similar irregularities of dimension 0.01 - 0.1 micron develop at the tip as well as on the conic part of the point.

This mentioned phenomenon sharply distinguishes boride from metals. It is well known that at approximately the same temperature (2000 - 2200°C) even in the refractory metals a considerable surface migration of atoms can be observed at the very tip of the point, which makes it smooth. It is possible that the irregularities are connected with the impoverishment of "near-the-surface" layers of lanthanum. This calls for the reconstructing of connections between knots (?) of the lattice and creating a new substance, for example LaB_{12}.

Of course, the surface structure must also change with it. Absence of migration proves the stability of the new lattice. Furthermore one can assume that the work function must also change, although in view of the strong geometrical irregularities, it is difficult to prove with auto-electronic methods.

Due to the complexity of surface processes in changing boride, we have no success at the present time in preserving the form of the emitter, which it received after the etching.

2. Emission pattern and adsorption properties

From the point of view of auto-electronic emission it is very important that the cathode is not coated, as the adsorptive layers are displaced very easily by ions.

As is known, the mechanism of emission of LaB_6 is explained variously: Lafferty[1] considers it a coated cathode, and Samsonov, Neshpor and Kuguntsev[2] - not coated (that is: low work function inherent in the substance itself). We assume the emission pattern observed on the screen of the projector could help solve the problem.

Illustration 4-a is an emission pattern of a cold point, and illustration 4-b a point from LaB_6 heated to 850°C.

Illustration 4. Emission pattern of the point.
a - cold point; b - at 850°C.

In Illustration 4-a is no structure; all that can be seen is only a fluctuating pattern of adsorption. This could be explained as a coated cathode, if it were not known that pure metals also can give a similar pattern in a cold state.

In heating the point, its surface is cleared from adatoms, the current increases and there distinctly develops a cubic crystal structure, characteristic for LaB_6 (Ill. 4-b). Characteristic crystallographic planes are shown in the illustration. As the current accelerates, the adsorption film, which can be observed in Ill. 4-a, increases the work function and it obviously is not the film of lanthanum.

Transformations of emission patterns are exactly the same as in case of metals. Hence it can be concluded with confidence that LaB_6 does not appear as a coated cathode. Besides, LaB_6 is apparently inclined to oxygen contamination, evidence for which includes, besides emission patterns, a series of volt ampere characteristics of the cold cathode, which were taken satisfactorily after heating the emitter, and then after 10, 20, 60, 90 min. (Ill. 5-a). Obviously, the work function continually increases.

In Ill. 5-b are shown the same characteristics for the heated emitters (850 - 900°C), which were taken after 60 and 90 minutes, one after the other. In the region of high voltage, the characteristics coincide, which proves the absence of contamination in the given case (at low voltage appears a fluctuation in temperature).

Illustration 5. Characteristics ln i = f(t/u) of point. a - cold; b - at temp. = 800 - 900°C. Curve 1 - directly after heating the emitter; 2, 3, 4, 5 - after 10, 30, 60 and 90 minutes correspondingly; X - directly after heating; ■ - after 60 minutes; ⊙ after 90 minutes.

Illustration 6 shows a typical dependence of emission current on time, at continuous current (curve 1) and with episodical switching on (curve 2). As the curved lines are close to each other, so here too the falling current cannot be explained by the combination of an active film directly with ions. Again the decisive factor is the contamination.

Illustration 6. Dependence of the emission current on time with continuous current (curve 1) and during the episodical switching on of voltage (curve 2).

Illustration 7 shows the emitter's volt-ampere characteristics, directly after prolonged heating at T ≃ 1500°C, then again after 15 minutes and again directly after the next heating at 850°C.

From Ill. 7 it appears first that the work function increases by 60 - 70% with contamination and, secondly, the principal mass of adsorbed gases withdraws at ~850°C.

Illustration 7. Characteristics ln i = f (i/u): O - directly after heating; X - after 15 minutes; ▼ - directly after the second heating to 850°C

In conclusion let us mention that the prolonged and strongly heated emitters hardly show any contamination. This interesting fact gives evidence of either the influence of internally dissolved gases, or the change of adsorption property while cleaning the surface, or, lastly, structural changes which have been mentioned earlier.

3. Temperature Dependence of Auto-electronic Current

Dependence of auto-electronic current on temperature for LaB_6 shows behavior which is typical of metals, as has been observed before. For boride, as a result of low work function, deflection of the characteristics ln i = f(i/u) from the straight line are observed with relative low temperatures. Temperature dependence is shown in Illustration 8.

Illustration 8. Changing of characteristics
$\ln i = f(i/u)$ with temperature.

4. Impulse Tests

Impulse tests were conducted by us with emitters first of all with the purpose to study their behavior during high current density. In various tests were observed currents 0.2 - 1 a at 9 - 20 kv and at pulse lengths 3 microseconds and at frequency 300 sec^{-1}. The corresponding current density amounted to $\sim 10^7$ a/cm^2. These mentioned currents could be observed for some time without their changing their magnitude.

In the process of tests were confirmed also the well known observations of Dyke about the strong currents near the vacuum arc, about the spreading of the local arc, which arises at a definite place on the surface of the emitter, to its whole surface, and also about the disappearance of the dark edges on the emission pattern.

The second problem of impulse tests is the utilization of the vacuum arc giving the emitter a definite shape with the purpose of subsequently determining the work function. It has been shown, that with this method one can systematically get smooth, nearly spherical, surfaces, but with considerable diameters (~10 microns), which is not always desirable.

Of special interest appear tests of emitters in stationary condition. It is possible to observe for some time unalterable currents (5 - 10 ma), which noticeably distinguishes the behavior of boride from that of metals.

5. Ion Bombardment

Tests of the stability of boride against ionic bombardment were the main purpose of the present research. Corresponding with the earlier described method[4] the dependence $u(t)$ at $i = \text{const.}$ was observed with different vapor pressures of mercury

Illustration 9 shows curves $u/u_o = f(t)$ under mercury vapor pressure p from 10^{-7} to 3×10^{-5} mm Hg. On this same illustration are shown identical curves for tungsten and rhenium.

A greater characteristic peculiarity in curves $u(t)$ for boride is the absence of the regions of decrease, even under relatively very high pressures, which proves the absence of the characteristic sharpening of the emitters, that is, the greater stability against ionic bombardment, considerably exceeding the stability of tungsten as well as rhenium. This rise in voltage must be attributed to the contaminated surface of boride with oxygen, which is always in the atmosphere of mercury vapor. For illustration of this thought is curve 8, for tungsten. This also shows the rise in $u(t)$, caused by contamination, which replaces the drop in $u(t)$, caused by sharpening of the emitter.

The end result appears very promising. The research in cathode sputtering of borides must spread,and broaden experimentally and theoretically.

Illustration 9. Dependence $u/u_o = f(t)$, where u is voltage on the instrument at a moment t, with u_o at $t = 0$; for i = const = 30 microamps, for various mercury vapor pressures.

6. Current-voltage Characteristics

A considerable amount of the current-voltage characteristics taken by us in the form $\ln i = f(i/u)$ differed from straight lines, which are characteristic for auto-electronic emission of metals.

At the beginning we interpreted such characteristics as evidence of a difference from metals of the emission mechanism of LaB_6. Subsequently it was explained that in a number of cases the reason of deflection from straight lines appears to be the above described cathode contamination during the taking of these characteristics (formed with the accepted method 5 - 10 seconds).

The utilization of a line oscillograph to measure the characteristics allowed us to shorten the time to take these characteristics to 0.2 - 0.3 sec. In this case the volt-ampere characteristics for LaB_6 always appear as straight lines (Ill. 10).

Illustration 10. True behavior of characteristic $\ln i = f(i/u)$

As has been indicated earlier, because of the complexity of determining the emitter form and the magnitude of the electric field on its surface, it is difficult to get reliable facts concerning the work function from auto-electronic measurements. All this is a series of estimations, done by us, leading to the important fact that the values are considerably smaller than was found in thermo-electronic measurements. It is possible that this is connected with the formation of a new phase (LaB_{12}) by extreme heat. This problem requires further study.

Conclusion

The established great stability of LaB_6 against ionic bombardment, and also the possibility of obtaining large steady and impulse currents, proves the great advantages of LaB_6 over metallic auto-electronic emitters.

It appears of great importance to do research in auto-electronic emissions of other refractory compounds, and, first of all, those which have a lower work function than LaB_6.

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